

t8code - modular adaptive mesh refinement in the exascale era

Johannes Holke¹, Johannes Markert^{1*}, David Knapp^{1*}, Lukas Dreyer^{1*}, Sandro Elsweijer^{1*}, Niklas Böing^{1*}, Ioannis Lilikakis^{1*}, Jakob Fussbroich^{1*}, Tabea Leistikow^{1*}, Florian Becker^{1*}, Carsten Burstedde², and Achim Basermann¹

¹ German Aerospace Center (DLR), Institute of Software Technology, Department High-Performance Computing, Cologne, Germany ² Rheinische Friedrich-Wilhelms-Universität Bonn, Institute for Numerical Simulations and Hausdorff Center for Mathematics, Germany ¶ Corresponding author * These authors contributed equally.

DOI: [10.xxxxxx/draft](https://doi.org/10.xxxxxx/draft)

Software

- [Review](#)
- [Repository](#)
- [Archive](#)

Editor: [Open Journals](#)

Reviewers:

- [@openjournals](#)

Submitted: 01 January 1970

Published: unpublished

License

Authors of papers retain copyright and release the work under a Creative Commons Attribution 4.0 International License ([CC BY 4.0](#)).

Summary

In this paper, we present our scalable dynamic adaptive mesh refinement (AMR) library t8code, which was officially released in 2022 (Holke et al., 2022). t8code is written in C/C++, open source, and readily available at dlr-amr.github.io/t8code. It is developed and maintained at the Institute for Software Technology of the German Aerospace Center (DLR). AMR is a widely used method of locally adapting the mesh resolution according to an adequate error indicator in grid-based applications – especially in the context of computational fluid dynamics. Our software library provides fast and memory efficient parallel algorithms for dynamic AMR to handle tasks such as mesh adaptation, load-balancing, ghost computation, feature search and more. t8code can manage meshes with over one trillion mesh elements (Holke et al., 2021) and scales up to one million parallel processes (Holke, 2018). It is intended to be used as mesh management backend in scientific and engineering simulation codes paving the way towards high-performance applications of the upcoming exascale era.

Statement of Need

Adaptive Mesh Refinement has been established as a successful approach for scientific and engineering simulations over the past decades (Babuvška & Rheinboldt, 1978; Bangerth et al., 2007; Dörfler, 1996; Teunissen & Keppens, 2019). By modifying the mesh resolution locally according to problem specific indicators, the computational power is efficiently concentrated where needed and the overall memory usage is reduced by orders of magnitude. However, managing adaptive meshes and associated data is a very challenging task, especially for parallel codes. Implementing fast and scalable AMR routines generally leads to a large development overhead motivating the need for external mesh management libraries like t8code. Our target audiences are scientists and application developers working on grid-based simulation and visualization frameworks who are looking for a comprehensive and versatile mesh management solution. Besides offering AMR we also aim to lower the threshold to parallelize their codes by solely interacting with t8code's API. Alternative AMR libraries with a similar range of features are p4est (Burstedde et al., 2011a), libMesh (Kirk et al., 2006), PARAMESH (MacNeice et al., 2000), and SAMRAI (Gunney, 2013).

In contrast to the other AMR solutions, only t8code natively supports recursive refinement on a wide range of element types: vertices, lines, quadrilaterals, triangles, hexahedra, tetrahedra, prisms, and pyramids. Additionally, extensions to other refinement patterns and element shapes

are straightforwardly supported due to t8code's modular code structure and clear distinction between low- and high-level mesh operations (Holke et al., 2023). Application developers usually interact with t8code via a callback interface. This gives our AMR solution an unique position in the market catering for a wide range of use cases. Currently, t8code is optimized for grid-based applications using face-to-face connectivity between elements, such as Finite-Volume and Discontinuous Galerkin methods. In the future, we plan to support node-to-node connectivity and hanging nodes resolution to further increase the range of applications, such as Finite Element methods. More information on t8code's feature set and on how to include it in an application can be found in (Holke et al., 2023).

Exemplary application

Figure 1 depicts an exemplary adapted mesh managed by t8code using two different element types: quads and triangles. Shown is the temperature profile of a convection simulation of a model planet's mantle (source: Institute of Planetary Research, DLR). The original, uniform mesh consists of over 158 million quad cells allocating 6.818 GB of memory. By applying AMR to the data the memory usage could be reduced down to 20% with a compression error of less than 1%. The error measure was chosen to be the norm of the variance between refinement resp. coarsening steps. That is, starting from the uniform mesh at highest refinement level ($l = 8$), the mesh was successively coarsened till the disagreement from the original data reached 1%. It should be noted that t8code's primary objective is to provide flexible adaptive mesh management. The layout of the data inside an element and its interpretation regarding, for example, when and how to refine/coarsen is up to the application.

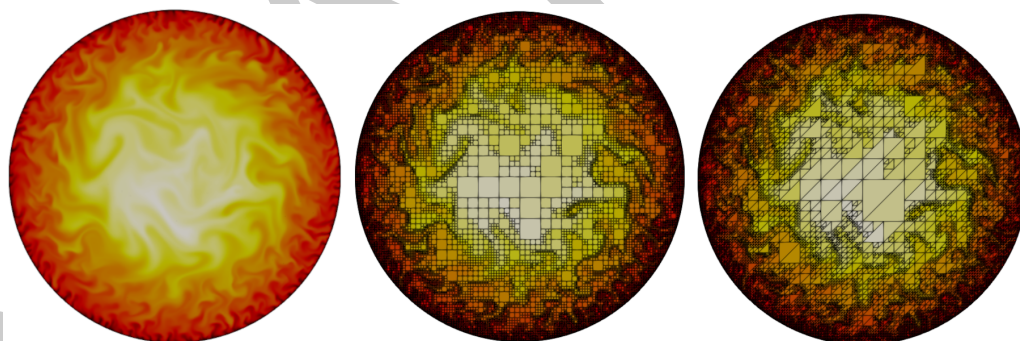


Figure 1: Visualization of a planetary mantle convection simulation (source: Institute of Planetary Research, DLR). Shown is the 2D slice of the temperature profile. Left: original uniform data. The highlighting of the grid lines was omitted for visual clarity. Middle: adapted mesh with quad elements. Right: adapted mesh with triangle elements. The original data living on a uniform quad mesh was first transferred to a triangle mesh and adapted afterwards. This shows the versatility of t8code regarding to the choice of mesh elements.

Fundamental Concepts

t8code is based on the forest-of-trees approach. Starting point for the usage of t8code is an unstructured conformal input mesh, which we denote a coarse mesh. This coarse mesh describes the geometry of the computational domain. Each of the coarse mesh cells is then viewed as the root of a refinement tree. These trees are refined recursively in a structured pattern, resulting in a collection of trees, which we call a forest. t8code stores only a minimal amount of information about the finest elements of the mesh - the leaves of the trees - in order to reconstruct the whole forest.

By enumerating the leaves in a recursive refinement pattern we obtain a space-filling curve (SFC) logic. Via these SFCs, all elements in a refinement tree are assigned an integer-based

73 index and are stored in linear order. Element coordinates or element neighbors do not need to
74 be stored explicitly but can be reconstructed from the SFC index. Fast bitwise SFC operations
75 ensure optimal runtimes and diminish the need for memory lookups. Moreover, the SFC is
76 used to distribute the forest mesh across multiple processes, so that each process only stores a
77 unique portion of the SFC. See [Figure 2](#).

78 While being successfully applied to quadrilateral and hexahedral meshes ([Burstedde et al.,](#)
79 [2011b](#); [Weinzierl, 2019](#)), these SFC techniques are extended by t8code in a modular fashion,
80 such that arbitrary element shapes are supported. We achieve this modularity through a novel
81 decoupling approach that separates high-level (mesh global) algorithms from low-level (element
82 local) implementations. All high-level algorithms can be applied to different implementations
83 of element shapes and refinement patterns. A mix of different element shapes in the same
84 mesh is also supported.

85 Mesh adaptation as it is done in t8code leads to hanging nodes. Numerical methods have to
86 specifically handle these non-conforming interfaces. Finite-Volume schemes or Discontinuous
87 Galerkin methods naturally treat this problem via so-called mortar methods. In the future, it
88 is planned to also support hanging nodes resolving routines by inserting transition elements
89 conformally connecting elements at different refinement levels.

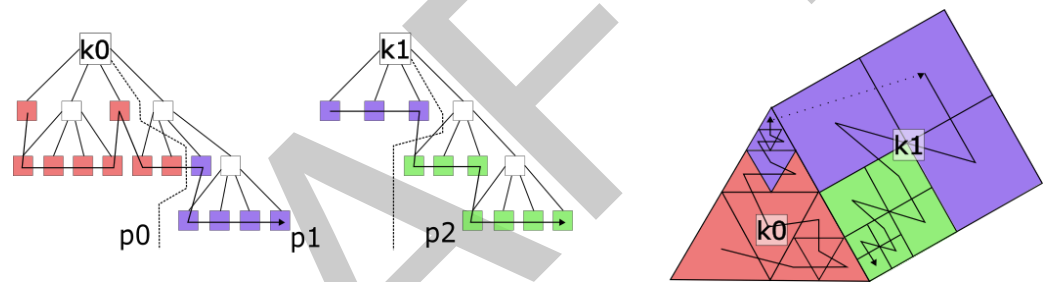


Figure 2: Left: Exemplary t8code forest mesh consisting of two trees (k0, k1) distributed over three parallel processes p0 to p2. The SFC is represented by a black curve tracing only the finest elements (leaves) of each tree. Right: Sketch of the associated mixed shape (a triangle and a quad) mesh refined up to level three.

Performance

91 t8code supports distributed coarse meshes of arbitrary size and complexity, which we tested
92 for up to 370 million coarse mesh cells ([Burstedde & Holke, 2017](#)). Moreover, we conducted
93 various performance studies on the JUQUEEN and the JUWELS supercomputers at the Jülich
94 Supercomputing Center. In [Table 1](#), ([Holke et al., 2021](#)) we show that t8code's ghost routine
95 is exceptionally fast with proper scaling of up to 1.1 trillion mesh elements. Computing ghost
96 layers around parallel domains is usually the most expensive of all mesh operation. Furthermore,
97 in a prototype code ([Dreyer, 2021](#)) implementing a high-order discontinuous Galerkin method
98 (DG) for advection-diffusion equations on dynamically adaptive hexahedral meshes we can
99 report of a 12 times speed-up compared to non-AMR meshes with only an overall 15% runtime
100 contribution of t8code. In [Figure 3](#) we compare the runtimes over number of processes of the
101 DG solver and the summed mesh operations done by t8code which are ghost computation,
102 ghost data exchange, partitioning (load balancing), refinement and coarsening as well as
103 balancing ensuring only a difference of one refinement level among element's face neighbors.
104 Additionally, from the graph we see the weak scaling property of the application, i.e. the
105 runtime halves when doubling the number of processes.

# Process	# Elements	# Elem. / process	Ghost
49,152	1,099,511,627,776	22,369,621	2.08 s

# Process	# Elements	# Elem. / process	Ghost
98,304	1,099,511,627,776	11,184,811	1.43 s

Table 1: Runtimes on JUQUEEN for the ghost layer computation for a distributed mesh consisting of 1.1 trillion elements.

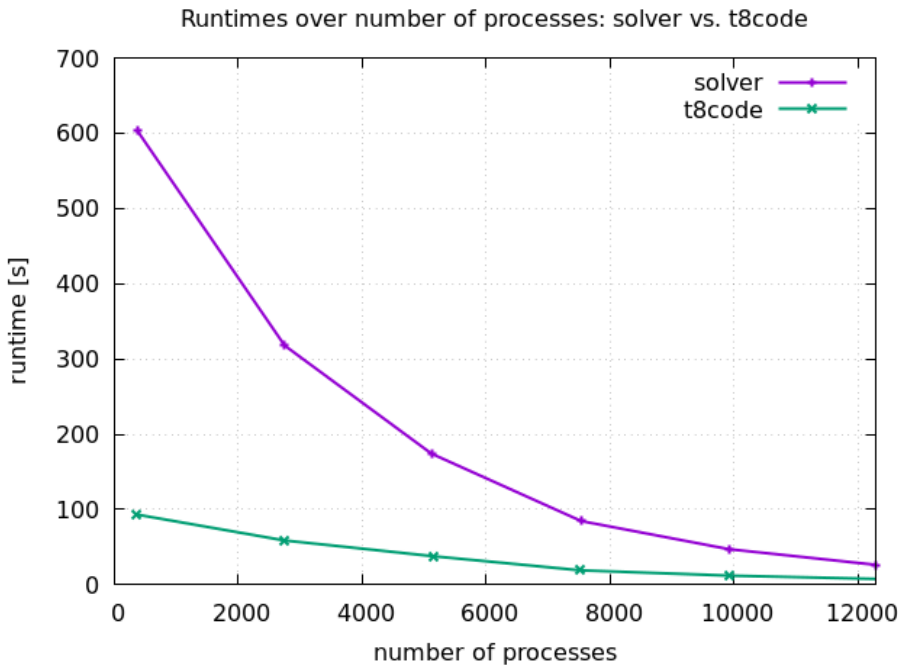


Figure 3: Runtimes on JUQUEEN of the solver and summed mesh operations of our DG prototype code coupled with t8code. Mesh operations are ghost computation, ghost data exchange, partitioning (load balancing), refinement and coarsening as well as balancing (max. difference of one level of refinement of neighboring elements). t8code only takes around 15% of the overall runtime. Additionally, we see the weak scaling property of the application, i.e. the runtime halves when doubling the number of processes.

Research Projects

Even though t8code is a newcomer to the market, it is already in use as the mesh management backend in various research projects, most notably in the earth system modeling (ESM) community. In the ADAPTEX project t8code is integrated with the Trixi framework (Schlottke-Lakemper et al., 2020) - a modern computational fluid dynamics code written in Julia. Over the next years several ESM applications are planned to couple to this combination, including MESSy, MPTrac, and SERGHEI. Moreover, t8code also plays an important role in several DLR funded research projects, e.g., VisPlore (massive data visualization), HYTAZER (hydrogen tank certification), and Greenstars (additive rocket engine manufacturing).

Further Information

For further information beyond this short note and also for code examples, we refer to our Documentation and Wiki reachable via our homepage dlr-amr.github.io/t8code and our technical publications on t8code (Becker, 2021; Burstedde & Holke, 2016, 2017; Dreyer, 2021; Elsweijer, 2021, 2022; Fußbroich, 2023; Holke, 2018; Holke et al., 2021, 2022; Knapp, 2020; Lilikakis, 2022).

Acknowledgements

Johannes Holke thanks the Bonn International School Graduate School of Mathematics (BIGS) for funding the initial development of t8code. Further development work was funded by the German Research Foundation as part of project 467255783, the European Union via NextGenerationEU and the German Federal Ministry of Research and Education (BMBF) as part of the ADAPTEX and PADME-AM projects. Development work was performed as part of the Helmholtz School for Data Science in Life, Earth and Energy (HDS-LEE) and received funding from the Helmholtz Association of German Research Centres. The development team of t8code thanks the Institute for Software Technology and the German Aerospace Center (DLR).

The authors state that there are no conflicts of interest.

References

- Babuvška, I., & Rheinboldt, W. C. (1978). Error estimates for adaptive finite element computations. *SIAM Journal on Numerical Analysis*, 15(4), 736–754. <https://doi.org/10.1137/0715049>
- Bangerth, W., Hartmann, R., & Kanschat, G. (2007). Deal.II—a general-purpose object-oriented finite element library. *ACM Trans. Math. Softw.*, 33(4), 24–es. <https://doi.org/10.1145/1268776.1268779>
- Becker, F. (2021). *Removing hanging faces from tree-based adaptive meshes for numerical simulations* [Master's thesis]. Universität zu Köln.
- Burstedde, C., & Holke, J. (2016). A tetrahedral space-filling curve for nonconforming adaptive meshes. *SIAM Journal on Scientific Computing*, 38, C471–C503. <https://doi.org/10.1137/15M1040049>
- Burstedde, C., & Holke, J. (2017). Coarse Mesh Partitioning for Tree-Based AMR. *SIAM Journal on Scientific Computing*, Vol. 39, C364–C392. <https://doi.org/10.1137/16M1103518>
- Burstedde, C., Wilcox, L. C., & Ghattas, O. (2011b). p4est: Scalable Algorithms for Parallel Adaptive Mesh Refinement on Forests of Octrees. *SIAM Journal on Scientific Computing*, 33(3), 1103–1133. <https://doi.org/10.1137/100791634>
- Burstedde, C., Wilcox, L. C., & Ghattas, O. (2011a). p4est: Scalable algorithms for parallel adaptive mesh refinement on forests of octrees. *SIAM Journal on Scientific Computing*, 33(3), 1103–1133. <https://doi.org/10.1137/100791634>
- Dörfler, W. (1996). A convergent adaptive algorithm for poisson's equation. *SIAM Journal on Numerical Analysis*, 33(3), 1106–1124. <https://doi.org/10.1137/0733054>
- Dreyer, L. (2021). *The local discontinuous galerkin method for the advection-diffusion equation on adaptive meshes* [Master's thesis, Rheinische Friedrich-Wilhelms-Universität Bonn]. <https://elib.dlr.de/143969/>
- Elsweijer, S. (2021). *Curved Domain Adaptive Mesh Refinement with Hexahedra*. Hochschule Bonn-Rhein-Sieg. <https://elib.dlr.de/143537/>
- Elsweijer, S. (2022). *Evaluation and generic application scenarios for curved hexahedral adaptive mesh refinement* [Master's thesis, Hochschule Bonn-Rhein-Sieg]. <https://doi.org/10.13140/RG.2.2.34714.11203>
- Fußbroich, J. (2023). *Towards high-order, hybrid adaptive mesh refinement: Implementation and evaluation of curved unstructured mesh elements* [Master's thesis, Technische Hochschule Köln]. <https://elib.dlr.de/200442/>

- 165 Gunney, B. (2013). *Scalable mesh management for patch-based amr*. Lawrence Livermore
166 National Lab.(LLNL), Livermore, CA (United States).
- 167 Holke, J. (2018). *Scalable algorithms for parallel tree-based adaptive mesh refinement with*
168 *general element types* [PhD thesis, Rheinische Friedrich-Wilhelms-Universität Bonn]. <https://doi.org/20.500.11811/7661>
169
- 170 Holke, J., Burstedde, C., Knapp, D., Dreyer, L., Elswijker, S., Uenlue, V., Markert, J., Lilikakis,
171 I., & Boeing, N. (2022). *t8code* (Version 1.0.0). <https://doi.org/10.5281/zenodo.7034838>
- 172 Holke, J., Burstedde, C., Knapp, D., Dreyer, L., Elswijker, S., Ünlü, V., Markert, J., Lilikakis,
173 I., Böing, N., Ponnusamy, P., & others. (2023). *t8code v. 1.0-modular adaptive mesh*
174 *refinement in the exascale era*.
- 175 Holke, J., Knapp, D., & Burstedde, C. (2021). An Optimized, Parallel Computation of the
176 Ghost Layer for Adaptive Hybrid Forest Meshes. *SIAM Journal on Scientific Computing*,
177 C359–C385. <https://doi.org/10.1137/20M1383033>
- 178 Kirk, B. S., Peterson, J. W., Stogner, R. H., & Carey, G. F. (2006). libMesh: A C++
179 Library for Parallel Adaptive Mesh Refinement/Coarsening Simulations. *Engineering with*
180 *Computers*, 22(3–4), 237–254.
- 181 Knapp, D. (2020). *A space-filling curve for pyramidal adaptive mesh refinement* [Master's
182 Thesis]. Rheinische Friedrich-Wilhelms-Universität Bonn.
- 183 Lilikakis, I. (2022). *Algorithms for tree-based adaptive meshes with incomplete trees* [Master's
184 thesis, Universität zu Köln]. <https://elib.dlr.de/191968/>
- 185 MacNeice, P., Olson, K. M., Mobarri, C., De Fainchtein, R., & Packer, C. (2000). PARAMESH:
186 A parallel adaptive mesh refinement community toolkit. *Computer Physics Communications*,
187 126(3), 330–354.
- 188 Schlottke-Lakemper, M., Gassner, G. J., Ranocha, H., & Winters, A. R. (2020). *Trixi.jl:*
189 *Adaptive high-order numerical simulations of hyperbolic PDEs in Julia*. <https://github.com/trixi-framework/Trixi.jl>. <https://doi.org/10.5281/zenodo.3996439>
190
- 191 Teunissen, J., & Keppens, R. (2019). A geometric multigrid library for quadtree/octree
192 AMR grids coupled to MPI-AMRVAC. *Computer Physics Communications*, 245, 106866.
193 <https://doi.org/10.1016/j.cpc.2019.106866>
- 194 Weinzierl, T. (2019). The Peano Software-Parallel, Automaton-based, Dynamically Adaptive
195 Grid Traversals. *ACM Transactions on Mathematical Software*, 45(2), 1–41. <https://doi.org/10.1145/3319797>
196